

Physico-mechanical properties of the sinter of various chemical composition

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Abstract. The paper includes data on the physico-mechanical properties of sinter of various origins including density (bulk, average, and true), porosity (open and total), critical angle of repose, internal and external angles of repose measured on dropping the material down onto a horizontal surface from a steel sheet inclined by 40°, 60°, and 80° to the horizon, angle of external friction on the steel surface, the strength properties of the sinter in a cold state and after reduction at a temperature of 500 °C. The investigated sinter had the following characteristics: an average density of 3.20–3.30 g/cm³; a true density of 4.43–4.57 g/cm³; an external angle of repose of 20.5–32.3 deg; a bulk porosity of 0.46–0.50 m³/m³; a degree of reduction by hydrogen at 500 °C of 3.3–4.8%. It demonstrated the following strength characteristics in the cold state: IR₊₅ = 92.0%, D_{0.5-5} = 5.5%, A_{0.5} = 2.5%. The strength characteristics after low-temperature reduction in hydrogen atmosphere were as follows: IR₊₅ = 29.80 %; D_{0.5-5} = 57.6 %; A_{0.5} = 12.6 %.

1. Introduction

Physico-mechanical and physico-chemical properties of iron ore raw materials loaded into a blast furnace determine the technical and economic indices of its operation [1–7]. The particle-size distribution of agglomerate, the repose angles of the loaded materials, as well as their bulk density, affect the distribution of components of the blast furnace charge along the radius and around the circumference of the furnace top [8–12]. Therefore, reliable information about these indices makes it possible to effectively regulate the loading of the blast furnace [13–19]. The porosity of materials is of high importance for the course of heat and mass transfer processes, including the reduction of iron and other elements from oxides [20–22]. Information on the porosity of sinter helps to analyze the movement of gases through the interparticle voids [23]. The strength characteristics of agglomerate, the share of fine fractions of less than 5 mm or 5–10 mm in it, affect the gas permeability of the stock column [24,25]; therefore, a number of recommendations and criteria have been proposed for the current operating conditions of blast furnaces [26]. Loading of the agglomerate having reduced physical and mechanical characteristics, a high content of the fine fraction, into the blast furnace operating with an upper limiting zone by gas dynamics, increases the mutual resistance of the charge and gas flows. This results in the suspension of burden and uneven run of the furnace, which will significantly reduce its productivity and raise the specific consumption of coke [27–29].

An analysis of the physico-mechanical characteristics of sinter makes it possible to develop a rational operating mode for a blast furnace. Using of such a mode provides the efficient application of agglomerated iron ore with various physico-mechanical properties and increases the technical and economic indices of smelting.



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2. Test material

For laboratory study, the samples of iron ore sinter having various chemical composition were taken. The chemical composition of the investigated samples of sinter are presented in Table 1.

Table 1. Chemical composition of the investigated samples of sinter.

No. of sample	Element/oxide content, wt %												Bas. ^a
	Fe	FeO	S	SiO ₂	CaO	MgO	Al ₂ O ₃	TiO ₂	P	Zn	Cr	MnO	
1	55.7	10.4	0.061	5.83	11.24	1.95	1.69	0.22	0.026	0.029	0.021	0.25	1.93
2	55.5	10.1	0.071	6.28	11.32	1.83	1.66	0.19	0.026	0.039	0.018	0.24	1.80
3	55.2	9.1	0.070	6.37	11.24	1.87	1.84	0.23	0.024	0.038	0.015	0.24	1.77
4	58.2	11.1	0.039	5.31	9.17	1.55	1.53	0.25	0.020	0.014	0.009	0.17	1.73

^a Basicity.

As can be seen from Table 1, the sinter sample No. 4 has an increased total iron content (58.2 % versus 55.2–55.7% for the samples No. 1, 2, and 3), which is due to the more advanced production technology that allows the use of up to 90% of the fine concentrates having an increased iron content in the sinter charge. The sinter sample No. 4 is also characterized by a lower CaO/SiO₂ ratio (1.73 versus 1.77–1.93 for the samples No. 1–3) and an increased content of iron oxide FeO (11.1% versus 9.1–10.4 %f or the samples No. 1–3).

3. Results

3.1. Grain-size composition

The particle-size distribution was determined by sieve analysis [30]. The results of sieve analysis are given in Table 2.

According to the table, the sinter sample No. 4 is characterized by the highest value of the equivalent surface diameter of particles. It is 27.0 mm versus 10.1–12.1 mm for the samples No. 1–3. The weighted-mean diameter of particles of the sinter sample No. 4 is also significantly higher than the weighted-mean diameter of particles of the other sinter samples and amounts to 34.7 mm compared to 17.9–23.9 mm for the samples No. 1–3. The sinter sample No. 4 is also characterized by the higher uniformity of particle sizes, which amounts to 0.78 against 0.44–0.62 for the samples No. 1–3.

3.2. Density and porosity

The determination of bulk, average and true density of the sinter was conducted for the sinter samples No. 1–4 [31].

The connected porosity of the sinter was determined by its saturation with water under vacuum [32]. The total porosity was calculated by determining the average and true density [31].

The bulk porosity of the sinter was calculated by bulk (ρ_{blk}) and average (ρ_{avr}) densities:

$$\varepsilon = 1 - \rho_{\text{blk}}/\rho_{\text{avr}} \quad (1)$$

The results of determining the density and porosity of the sinter are given in Table 3. According to the Table 3, the sinter sample No. 4 has an average density of 3.20 g/cm³, which is less than the average density of the samples No. 1, 2 and 3, the value of which is at the level of 3.27–3.30 g/cm³. Moreover, the true density of the sinter sample No. 4 is higher than that of the samples No. 1, 2 and 3 by 2.9 % on average.

The increased uniformity of particle sizes by 33% (Table 2) of the sinter sample No. 4, compared with the samples No. 1, 2, and 3, provided the sinter sample No. 4 with the highest bulk porosity of 0.50. The content of the fraction of 0–5 mm in the samples No. 1, 2, and 3 in the range of 5.4–9.9% with a uniformity of particle sizes in the range of 0.44–0.62 provided bulk porosity of 0.46–0.47, which is less than that of the sinter sample No. 4.

Table 2. Granulometric composition of the sinter from the samples No. 1–4.

Index name	Fraction content, wt %			
No. of sample	1	2	3	4
Size range, mm:				
80–100	–	–	5.82	–
60–80	4.63	–	1.35	8.16
40–60	11.05	6.62	7.26	19.76
25–40	19.62	11.24	14.26	44.23
10–25	43.29	50.39	38.30	26.53
5–10	13.85	26.41	23.12	0.53
0–5	7.56	5.35	9.89	0.8
Total	100	100	100	100
Size range (fine fractions), mm:				
7–10	43.13	56.90	45.97	47.76
5–7	21.56	26.26	24.08	12.42
3–5	16.71	8.36	17.51	9.55
1–3	7.55	2.54	7.09	9.55
0.5–1.0	2.26	1.34	1.40	5.06
0–0.5	8.79	4.60	3.94	15.66
Total	100	100	100	100
Equivalent surface diameter of particles, mm	12.14	11.09	10.11	26.90
Weighted-mean diameter of particles, mm	23.94	17.89	23.13	34.68
Homogeneity of the particle diameters	0.51	0.62	0.44	0.78

Table 3. Density and porosity of the sinter samples No. 1–4.

Index name	Index value			
No. of sample	1	2	3	4
Density:				
bulk, t/m ³	1.75	1.75	1.75	1.6
average, g/cm ³	3.30	3.30	3.27	3.20
true, g/cm ³	4.46	4.44	4.43	4.57
Porosity, %				
unconnected	26.0	25.6	26.2	29.9
connected	14.2	11.8	10.7	9.2
Bulk porosity, m ³ /m ³	0.47	0.47	0.46	0.50

3.3. Angles of repose and external friction

The angle of repose of bulk materials can be measured by a variety of methods the most widely used of which are: the tilting box method, the fixed funnel method, the revolving cylinder/drum method, the hollow cylinder method, and the tilting cylinder method. The difference between the angles of repose measured by various methods for the components of the blast furnace burden usually can be ignored. For the purposes of this study, the angle of repose was determined by the hollow cylinder method.

The outer and inner angles of repose of the sinter were determined by dropping it down from a height of 0.5 meters after moving along the surface of the steel sheet inclined at angles of 40°, 60°, and 80° to the horizon and having a length of 1 m. After the formation of an asymmetric pile both its angles to the horizon were determined characterizing external (the angle forming along the direction of movement of particles) and internal (the opposite angle) angles of repose correspondingly.

By raising the horizontally installed surface of the steel sheet with the sinter layer placed on it, the angle of external friction of the sinter on the steel surface was determined as the maximum angle at which the stationary state of the material is maintained.

The results of determining the angle of repose, the external and internal angles of repose in operating conditions and the angle of external friction on the steel surface are given in Table 4.

Table 4. Angles of repose and external friction for the sinter samples No. 1–4.

Index name	Index value			
No. of sample	1	2	3	4
Natural angle of repose, deg	32.3	34.3	33.0	33.6
Internal angle of repose (deg) determined by dropping the sinter down onto horizontal surface from the steel surface inclined to the horizon at an angle of, deg:				
40				
60	41.9	38.3	37.6	27.6
80	39.2	35.2	34.6	22.5
	39.7	42.6	36.8	25.2
Internal angle of repose (deg) determined by dropping the sinter down onto horizontal surface from the steel surface inclined to the horizon at an angle of, deg:				
40				
60	25.8	20.5	33.5	21.0
80	24.6	27.6	25.3	17.5
	32.3	34.9	28.3	21.8
External friction angle on the steel surface, deg	23	27	22	24

The strength of a suitable sinter expressed as resistance to impact loads and abrasion was determined by testing a sample weighing 200 g in a steel pipe with an internal diameter of 78.5 mm and a length of 1 m, rotating at a speed of 27 rpm, for 8 minutes. After testing the sample was sieved into three fractions, +5 mm, 0.5–5 mm, and –0.5 mm. The resistance of a suitable sinter to impact (IR_{+5}) was determined by the percentage of the fraction +5 mm, the destruction of a suitable sinter ($D_{0.5-5}$) – by the percentage of a fraction of 0.5–5 mm, abrasion of a suitable sinter ($A_{-0.5}$) – by the percentage of the fraction –0.5 mm [31].

The determination of the ‘hot’ strength of sinter, or the strength after reduction, was conducted as follows. The samples of sinter were crushed and sieved into a fraction of 10–15 mm and placed into an electric tube furnace. Reduction of the sample was carried out in the furnace by isothermal holding at a temperature of 500 °C in a stream of pure hydrogen (99.997%) for 1 hour. After cooling the sample in an inert medium (99.5% nitrogen) a drum strength test was conducted similar to the determination of the ‘cold’ strength of sinter.

The results of determining the ‘cold’ and ‘hot’ strength of the sinter are given in Table 5. The degree of reduction of the sinter tested for evaluation of the ‘hot’ strength is shown in Table 6.

Comparison of the indices of resistance to impact loads for a ‘cold’ suitable sinter from different plants shows that the sinter samples No. 1 ($IR_{+5} = 92.93\%$) and No. 4 ($IR_{+5} = 92.0\%$) have the highest values of impact resistance. The sinters No. 2 ($IR_{+5} = 88.56\%$) and No. 3 ($IR_{+5} = 88.38\%$) are less resistant to impact. The samples No. 3 ($D_{0.5-5} = 8.59\%$) and No. 2 ($D_{0.5-5} = 8.46\%$) are characterized by the greatest destruction in the cold state; the sinters No. 4 ($D_{0.5-5} = 5.50\%$) and No. 1 ($D_{0.5-5} = 5.05\%$) are less susceptible to destruction. The order of changing of abrasion for the investigated samples of sinters depending on the sample number is similar to the order of changing of destruction for these sinters. The sinter samples No. 3 ($A_{-0.5} = 3.03\%$) and No. 2 ($A_{-0.5} = 2.99\%$) are characterized by the greatest abrasion in the cold state while the sinters No. 4 ($A_{-0.5} = 2.50\%$) and No. 1 ($A_{-0.5} = 2.02\%$) demonstrate a much lesser degree of abrasion.

After reduction in hydrogen atmosphere, the strength characteristics of all the kinds of sinters studied in this work decrease to a different degree. Strength characteristics of the sinter sample No. 4 were especially strongly reduced. The resistance of a suitable sinter to impact loads measured by the content of the +5 mm fraction decreased from 92.00% to 29.80%, i.e., about 3.1 times. The destruction of a suitable sinter measured by the content of fraction 0.5–5 mm increased from 5.50% to 57.58%, that is, about 10.5 times. The abrasion of a suitable sinter increased from 2.50% to 12.63%, that is, about 5.1 times. The relative drop in the corresponding strength characteristics of the other samples of sinter was significantly lower. Its values were in the following ranges: for impact resistance – from 1.4 to 1.8; for destruction – from 3.4 to 7.9; for abrasion – from 2.0 to 3.2. Data on the degree of reduction

of the studied sinter samples, which are given in Table 6, indicate that the main reason for the sharp decrease in the strength characteristics of the sinter sample No. 4 after low-temperature reduction in hydrogen atmosphere is the increased reducibility of the material.

Table 5. ‘Cold’ and ‘hot’ strength of the sinter samples No. 1–4.

No. of sample	Strength indices, %					
	Resistance of a suitable sinter to impact (+5 mm)		Destruction of a suitable sinter (0.5–5 mm)		Abrasion of a suitable sinter (0–0.5 mm)	
	‘Cold’ strength	‘Hot’ strength	‘Cold’ strength	‘Hot’ strength	‘Cold’ strength	‘Hot’ strength
1	92.93	53.50	5.05	40.00	2.02	6.50
2	88.56	64.82	8.46	29.15	2.99	6.03
3	88.38	49.75	8.59	42.21	3.03	8.04
4	92.00	29.80	5.50	57.58	2.50	12.63

Table 6. Degree of reduction of the sinter tested for evaluation of the ‘hot’ strength and its FeO content.

No. of sample	Degree of reduction, %	FeO content, %
1	3.3	16.34
2	3.3	16.64
3	3.3	15.92
4	4.8	20.51

4. Conclusions

The differences in the physico-mechanical properties of the sinter sample No. 4, compared with the sinter samples No. 1–3, are as follows:

- its average density of 3.20 g/cm³ is higher than the average densities of the sinter samples No. 1, 2, and 3, the values of which are at the level of 3.27–3.30 g/cm³;
- the true density is increased by 2.9%;
- the internal angle of repose of 34.6% and external angle of repose of 28.4% are lower than the ones for the other sinter samples;
- the highest bulk porosity –for the samples No. 1, 2, 3, and 4, its values are 0.47, 0.47, 0.46, and 0.50 m³/m³, respectively;
- the reducibility in hydrogen atmosphere at a temperature of 500 °C is increased by 1.5% (abs.) in comparison with the sinter samples No. 1, 2, and 3;
- high strength characteristics in the cold state, IR₊₅ = 92.00%; D_{0.5-5} = 5.50%; A_{0.5} = 2.50%, and relatively low strength characteristics after low-temperature reduction in hydrogen atmosphere: IR₊₅ = 29.80%; D_{0.5-5} = 57.58%; A_{0.5} = 12.63%, due to the high reducibility of the material.

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